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***Highlights (for review)**

Highlight section:

- Overheating in UK Passivhaus dwellings
- Individual spaces overheating percentage in comparison to the entire building average
- Window opening patterns and lack of night time cooling
- Summer bypass option and its impact on overheating percentage
- Internal heat gain implication and calculations
- MVHR fresh air intake location and surrounding material properties and its impact
- Incoming fresh air temperature from MVHR during the summer in relation to outdoor temperature

An investigation into causes contributing to summer overheating in UK Passivhaus dwellings

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Abstract

Designing and building to higher efficiency standards like Passivhaus can have an effect on possible overheating during the summer. The impact of internal heat gain and window operation alongside use of MVHR can be higher in such buildings due to high levels of insulation and airtightness. The continuous use of MVHR during the summer and summer bypass option together with the location of the intake and material properties surrounding the intake was investigated as well as window operation. Two case study buildings were monitored, built to Passivhaus and EnerPhit standards, one lightweight and the other with thermal mass. The indoor temperatures during the summer of 2014 were recorded together with the incoming fresh air at the MVHR outlet and the local temperature surrounding the intake externally, along with the duration of window operation. PHPP was used to examine the effect of summer bypass and internal gains. The monitoring results highlighted the importance and effect of the MVHR intake location and duct insulation alongside the reliance on summer cooling using windows especially during the night in respect to summer overheating which

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Key words:

Passivhaus, Overheating, Natural ventilation, Monitoring, MVHR, Summer bypass, PHPP

1. Introduction

Passivhaus standard emerged around 25 years ago from Germany and quickly expanded to not only Western Europe but also worldwide with over 50,000 buildings constructed using the Passivhaus standards (Cotterell & Dadeby, 2012) (IG Passivhaus, 2013). Since the introduction of Passivhaus standard and certification in the UK around 2010 (McLeod, Hopfe, & Kwan, 2013), the standard has been rapidly endorsed and is helping to achieve the UK government target of 80% reduction in CO_2 emissions by 2050, which was passed into law on the 28th of October 2008 (HMSO, 2008).

Traditionally the UK climate conditions increases the emphasis more towards the winter period and consequently the heating requirements for buildings. Passivhaus standard, therefore, with a high level of insulation and airtightness could be an ideal candidate for providing high standards of thermal comfort during the UK winter. The heating requirement for Passivhaus which is defined as ‘Specific Space Heating Demand’ is the total heating required for the building for the entire year and needs to be equal to or below 15kWh/m^2 per annum. The specific space heating demand is calculated for the internal habitable area of the building called Treated Floor Area (TFA) not to be mistaken for gross internal floor area which is commonly used in the UK. The German standard of WoflV and Din 277 is used for defining the calculation of TFA and for instance excludes the internal walls as well as staircases which are more than three steps (Lewis, 2014).

Due to recent recognition of the difficulties of achieving Passivhaus standard for existing buildings (e.g. cold bridging from the internal walls), EnerPhit certification was developed by Passivhaus Institute. The EnerPhit standard is slightly less stringent for specific space heating demand and is set at ≤ 25kWh/m^2 alongside a lower airtightness level of 1 air change per hour at 50 Pascal pressure in comparison to 0.6 air change/h for Passivhaus (Passive House Institute & RoA Rongen Architects GmbH, 2011).

In both Passivhaus or EnerPhit standards, the internal heat gain is calculated using a standard value of 2.1W/m^2 which ensures that the specific space heating demand is not underestimated and additional losses not accounted for, such as heat sink from the cistern refilling and towels drying, are taken into consideration (Passive House Institute, n.d.). However the latest calculation procedures for the internal heat gain introduced by the institute, separates the internal gains for winter and summer. The winter internal heat gain uses the previous standard value of 2.1W/m^2 while the summer internal heat gain is calculated from the sum of all additional gains, like the use of MVHR during summer, to ensure extra heat loads are taken into consideration.

Calculating the internal heat gain for the summer as well as all the other requirements for designing and certifying a Passivhaus building can be undertaken by using Passivhaus Planning Package (PHPP) which is an Excel workbook with several inter connected sheets. PHPP was initially published in 1998 and has had track records of high-levels of accuracy in energy balance calculations of up to +/-0.5kWh/m^{2}a (Lewis, 2014). Moreover PHPP has been cross examined using actual data from monitored buildings as well as dynamic simulation programme, Dynbil (McLeod et al., 2013).

The verification sheet in PHPP provides a quick summary for the building which includes heating and cooling requirements, primary energy demand, airtightness and the frequency of the overheating for the building. The overheating limit for Passivhaus is set to 25°C and the maximum percentage that the building can go over this limit is set at 10% (Passivhaus Institut, 2012). However the 10% is the maximum allowable limit and aiming more towards 5% or even 4% is encouraged by Passivhaus institute especially when taking the change in climate into consideration (Passivhaus Institut, 2012).

The ventilation requirements can be calculated by the aid of the Ventilation and SummerVent sheet from PHPP which is an essential part of the building design and this is no different for Passivhaus buildings and if anything even more important due to their high level of airtightness. The ventilation in the UK dwellings is generally achieved through the use of windows during the summer and trickle vents throughout the colder periods of the year, in addition to the infiltration through the building fabric (Pennycook, 2009). The use of trickle vents during the winter is not without the additional energy and heating requirements as well as the possible occupant discomfort caused by the incoming cold air (Passivhaus Institut, 2012)

The Passivhaus standard targets the airtightness levels of the building as well as the ventilation strategy for the winter period in order to reduce the energy required for the heating. This has been extended further to optimise the occupant's thermal comfort by requiring a minimum 17°C of incoming fresh air during the winter when the ambient temperature is as low as -10°C (Schnieders, 2009). Passivhaus uses DIN 1946-6 and EN 13779 standard for ventilation requirements and aims to keep the indoor CO_2 level below 1000ppm with relative humidity between 35% and 55% (Cotterell & Dadeby, 2012).

The winter ventilation requirements of Passivhaus would not be easily achievable for the UK climate, taking all the other Passivhaus standards into account, without the aid of a highly efficient MVHR unit. The MVHR is required to have a minimum 75% efficiency and a maximum electrical efficiency of ≤0.45Wh/m^3 in order to achieve 20-30 m^{3}h^{-1} of air change per person under the standard and not fall below 0.3 h^{-1} of air change related to the net volume (Passive-On, n.d.).

The use of MVHR is normally continuous throughout the year in Passivhaus buildings as during the warmer time of the year, the need for extraction from the wet areas still exists in addition to provision of the minimum levels of fresh air for occupants, if windows are not used. However there is no requirement for the unit to benefit from bypass option during the summer period under the Passivhaus standards (Passive House Institute, 2007). Therefore when the MVHR is operational during the warmer time of the year and the benefit of the heat exchanger is non-existent, the lack of bypass option could contribute to extra heat gain. In addition during the summer period, the MVHR is no longer as efficient since the building is being conditioned by the means of mechanical ventilation with no other extra benefit.

The ventilation sheet in PHPP allows the user to specify and input all the required information regarding the building ventilation. Whereas the summer ventilation sheet provides the extra information regarding the summer bypass option as well as calculations for window openings (Lewis, 2014).

The summer ventilation sheet in PHPP8 was revised from the previous version (PHPP7) considerably to include the following new options in regards to summer bypass option which has been kept in PHPP9:

- None (Always by-pass or pure supply air ventilation unit)
- Automatic by-pass, controlled by temperature difference
- Automatic by-pass, controlled by enthalpy difference
- Always (no by-pass)

In addition, the Passivhaus standard does not make reference to the exact location of the MVHR intake and extract in regards to orientation, shading, material surrounding the intake and extract, distance from one another and the insulation around the ducts after the MVHR unit if no post heater is being used (Passivhaus Institut, 2012).

Designing low energy buildings with a high level of insulation and airtightness with large south facing glazing, helps in reducing the heating demand during the winter, but can increase the potential for summer overheating (Richard Partington Architects, 2012). This concern has been increasing in recent years as higher temperature during the summer is experienced and expected to increase further in the near future (Intergovernmental Panel on Climate Change, 2014). However other causes could also contribute to the overheating potential in ultra-efficient buildings such as the position of the MVHR inlet and lack of window operation especially during the night.

Post occupancy evaluation carried out on Passivhaus dwellings has identified the potential of overheating across Europe and more recently the UK. Monitoring of Camden Passive House in London for instance recorded 22.5% over the 25°C limit in the living room and identified low ventilation of 0.14ac/h during the summer by the use of windows (Ridley et al., 2013). Likewise the BUS survey (Building Use Studies) carried out on 21 bungalows (Racecourse estate) highlighted a similar problem which was put down to lack of window operation especially at night influenced by security and noise concerns (Siddall, Johnston, & Fletcher, 2014).

The objective of this study is to investigate the effect of window operations on overheating potential and examine the specific overheating percentage for each area of the building which could be underestimated due to averaging the total overheating percentage for the building in PHPP. Moreover the impact of the summer bypass option on two case study buildings was re-examined and the possible impact on the incoming fresh air temperature in regards to orientation and the microclimate surrounding the MVHR intake and extract was investigated.

2. Materials & Methods

Two case study buildings in England constructed during 2011 and 2012 were selected for monitoring. The first is a new domestic residence built to Passivhaus standards and the second is a home extended and refurbished to EnerPhit standards. The monitoring was done during the summer of 2014 and the parameters of interest include: indoor temperatures; relative humidity; CO_2 levels; and the daily operation of windows.

The monitoring period for the buildings included May and September in addition to the summer months of June, July and August. This was to ensure that a wider range of monitored data would be available in the context of the adjacent cooler months. Furthermore both buildings were originally designed and certified using PHPP7 which at the time of this research had been updated by Passivhaus Institute to PHPP8. The revised PHPP takes the possible higher internal gains during the summer into account by allowing the user to input and calculate the summer internal gains, alongside some other small changes (Passive House Institute, 2013). Therefore recalculation was carried out in order to: examine the effect of higher internal gain on summer overheating using PHPP8; include an updated equipment schedule; incorporate additional shading from the completed buildings as well as examining the effect of summer bypass option. The recalculation data using PHPP8 was consequently compared to the actual data and further adjustments were made.

The majority of spaces in the thermal envelope were included for monitoring the indoor temperatures except the corridors and storage spaces. The data loggers used were HOBO U10 and U12 which also provided the opportunity to include the indoor relative humidity (RH) in addition to temperatures. They were placed generally at a height of around 800mm to 1000mm from the floor within the ASHRAE standard 55 requirement (Jakob et al., 2004), away from direct solar radiation and any internal heat sources. Where possible door frames were used in order to reduce any possible damage caused by the sticky Velcro used in securing the loggers in place. To ensure high resolution in monitoring data, the loggers were set to record every 15 minutes throughout the five months of monitoring. The diagram below comparatively illustrates the spaces monitored in the two case study buildings.

Figure 1- Monitored rooms in the case study buildings

Small data loggers (I-Buttons) were also located inside the MVHR outlet in the main bedroom as well as the living room, in order to monitor the incoming fresh air temperatures from the MVHR. The data loggers were placed inside the MVHR duct close to the room outlet and set to record every hour.

Moreover for ambient hourly temperatures, British Atmospheric data centre (BADC) was used. Two locations were identified from the available stations in the BADC (very close to the locations of the two buildings) which one is the exact same as per the climate data used in PHPP (from Meteonorm) and the other is a few metres away from the second location.

A thermal imaging camera was also used to capture the surface temperature of the material around the MVHR air intake and extract. The thermal performances of surface materials used adjacent to the MVHR air intake and extract were examined with respect to temperature of the mass of materials using data from the thermal imaging camera. During the 16th and 17th July 2014 as the ambient temperatures were warmer and mostly sunny, the surface temperature of the materials were measured every hour from 9:00am until 10:00pm. Consequently the measurements were compared to the ambient and the indoor temperature alongside the data from the loggers placed inside the MVHR air outlet. This allowed the possibility to examine the effect of lack of insulation surrounding the MVHR ducts internally alongside the impact of the location and the material adjacent to the intake on the possible overheating in the two case study buildings.

The indoor CO_2 levels were monitored using Telaire 7001 CO_2 sensors in conjunction with HOBO U12 used to examine the ventilation rate of the two case study buildings. Finally, window operations were documented using a combination of HOBO U9 state loggers and magnetic window sensors. These allowed recording of both duration and frequency of openings for selected windows. The functionalities of these sensors did not allow monitoring of the angle of opening for the windows, whether they were opened on tilt or turn.

Based on frequency of use (as confirmed by occupants), nine windows and patio doors were selected from each of the buildings to be monitored. Although the window sensors were secured to the window frames using double-sided sticky tape (ensuring minimum damage to the frames), some data losses occurred due to sensors not staying in place which further led to reinforcement of the fasteners.

2.1. Description of the two case study buildings

Building One (Passivhaus) was constructed in 2011 with mainly lightweight construction materials over three floors and comprises of five bedrooms. The building benefits from a high level of airtightness above Passivhaus requirement and was tested to be 0.07 air change at 50 Pascal. As mentioned previously, PHPP7 was used for the design and certification purposes with “Thames Valley” being the weather data generated by the BRE for PHPP (McLeod, Hopfe, & Rezgui, 2012).

The building’s TFA (treated floor area) is just over 182m^2 and the ventilation volume (V_v) was measured to be 455m^3. The standard internal gains from PHPP7 of 2.1W/m^2 had been used for the design and certification purposes. Moreover the specific space heat demand was calculated to be 11kW/(m^{2}a) with no frequency of overheating during the summer period.

The building is occupied by a family of three which is lower than the PHPP standard occupancy level of around 35m^2 per person (Passive House Institute, 2007). The 35m^2 per person PHPP standard equates to just over five persons for this building which was also used during the design and commissioning of the MVHR. The MVHR used for this building is ‘Zehnder-Comfoair 550’ which is certified to be 84% efficient located inside the thermal envelope in the second floor cupboard which can be accessed from the shower room. The internal ducts after the MVHR unit are not insulated and the inlet is through the Northeast wall with outlet through the roof. The unit benefits from summer bypass option set at 21°C and the unit is operational all year round.

Building Two (EnerPhit) was refurbished and extended on the first floor to Passivhaus EnerPhit standard and was completed during 2012 with a TFA of 173.2m^2. The existing walls have been insulated externally and between the cavities, with wet plaster finish internally providing the airtightness layer, maintaining the thermal mass of the existing building. The building's ventilation volume (V_v) was calculated to be 433m^3 and the airtightness test of the completed building met the EnerPhit standard of 1 air change rate at 50 Pascal pressure. The climate data used from PHPP was "Midlands" and like the first building the internal gains used for the design and certification, was the standard 2.1W/m^2 from PHPP7. The building's specific heating demand was calculated to be below the requirement of 25 kWh/(m^{2}a) for refurbishment and the heating load of 14 W/m^2 with no overheating. The actual occupancy for this building is four persons closer to the value of just below five calculated from PHPP.

The EnerPhit building's MVHR is 'PAUL novus 300' with certified efficiency of 93%, located in the loft space (part of the thermal envelope) used as storage with no external glazing. As per the first building, the internal ducts leading from the MVHR unit are not insulated. The air inlet and outlet are through the Northeast wall stacked one above another with the outlet being lower than the inlet increasing the potential of short circuiting and contamination of the incoming fresh air. The MVHR summer bypass option is set at 23°C and the MVHR is used throughout the year. The table below compares the two buildings in respects to their size, occupancy and the calculated component U-Values.

Table 1- Comparison of reference buildings' data

	TFA m²	Vv m³	Occupancy PHPP/ Actual	Walls U-Value	Roof U-Value	Floor U-Value	North window U-Value	East window U-Value	South window U-Value	West window U-Value
Building 1	182	455	5 / 3	0.137 W/m²K	0.113 W/m²K	0.100 W/m²K	0.876 W/m²K	0.850 W/m²K	0.834 W/m²K	0.950 W/m²K
Building 2	173.2	433	5 / 4	0.101 W/m²K	0.109 W/m²K	0.139 W/m²K	0.850 W/m²K	0.878 W/m²K	0.890 W/m²K	0.878 W/m²K

The following table is the summary information from the PHPP regarding the glazing area, g-Value and the average global radiation from the climate data.

Table 2- Comparison of reference buildings glazing information

	g-Value		Window area m²		Glazing area m²		Average global radiation	
	B 1	B 2	B 1	B 2	B 1	B 2	B 1	B 2
North	0.52	0.53	8.62	1.21	4.4	0.8	91	83
East	0.60	0.53	15.54	20.97	10.7	12.7	243	213
South	0.62	0.53	25.72	4.73	18.7	2.9	377	326
West	0.52	0.53	1.32	12.99	0.5	7.6	160	144
Total			51.19	39.90	34.3	24.0		

Building One benefits from a larger total window, and therefore, glazing area with around 10m^2 difference (Table 2). The majority of the windows are located in the South and East façade for Building One whereas Building Two's windows are mainly situated in the East and West façade. Horizontal glazing is non-existent in either of the buildings and all windows are operated using tilt and turn system.

3. The monitoring results

Monitoring was completed at the beginning of October 2014 and data collated and analysed showed that Building One (Passivhaus) was found to be generally experiencing high temperatures during the monitored period. The frequency that the temperatures exceeded the 25°C limit for overheating during the five months of monitoring was over 50% translating to around 21% of the year, assuming no further overheating incidences would occur. On the other hand the Building Two's (EnerPhit) indoor temperatures were lower and the overheating percentage during the five months was 0.65% translating to 0.26% of the year if no further overheating was recorded. However it could be suspected that some effort was made by the occupant to prevent possible overheating, not only due to the nature of this research but also as overheating had been experienced during the previous summer.

It should be noted that overheating calculation from PHPP is based on the average of the entire building for the whole year (Passivhaus Institut, 2012) and not necessarily on the individual spaces which could lead to a higher potential of overheating in a specific room. This could be overlooked when using PHPP and therefore the monitoring result was calculated for the individual areas, the average for each floor as well as for the entire building(s).

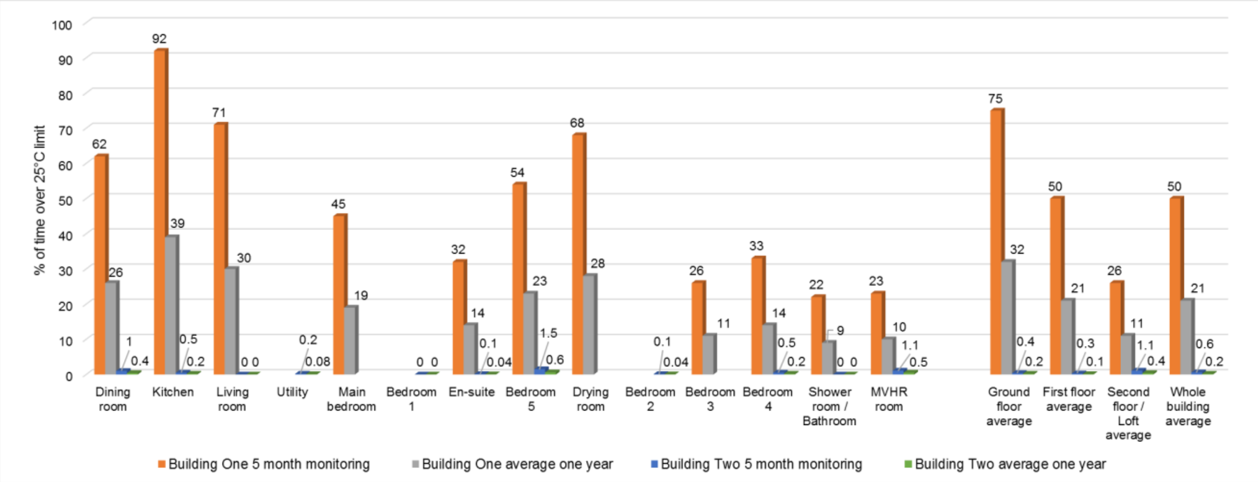


Figure 2- Overheating percentage for different rooms and period

High percentage of overheating for the individual spaces in Building One during the five months of monitoring was observed (Figure 2) reaching as high as 92% in the kitchen (it should be noted that the logger in the kitchen was placed over 1m high due to lack of available space). Whereas the average of the entire building for the whole year is much lower at just over 21%. Furthermore an examination of different floors' average overheating percentage, indicates higher temperatures on the lower floors in comparison to floors above which is true for both buildings but on a different scale. This phenomenon might be influenced by the positioning and the area of the glazing in the different floors, however it also highlights that the heat from the lower floors did not necessarily rise to the higher floors which could be put down to the very airtight envelope of Passivhaus buildings.

The decision to monitor the indoor CO_2 levels as mentioned earlier was to examine the effectiveness of the ventilation strategy specifically for the warmer periods of the year. Close examination of the monitored indoor CO_2 levels (Figure 3) highlights similar scenarios for the living rooms and main bedrooms of both buildings. The CO_2 levels in living rooms were almost always below the limit or above the 1000ppm for a very small percentage of the time. This was truer for the warmer months of the year when the windows were also operated in conjunction with the MVHR. However the recorded CO_2 levels for the main bedrooms, where two adults slept, was mostly over the limit during the night. The higher CO_2 levels in the main bedroom could indicate that insufficient rates of ventilation were delivered by the MVHR and also influenced by the lack of window operation in this period, specifically at night.

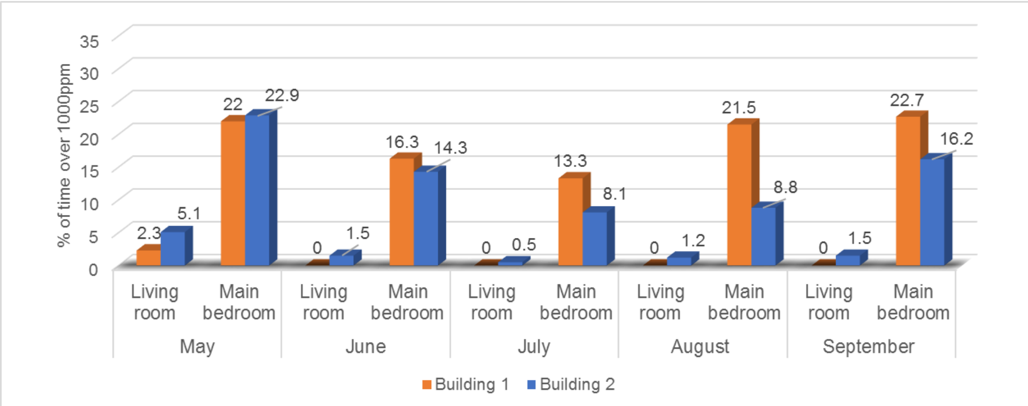
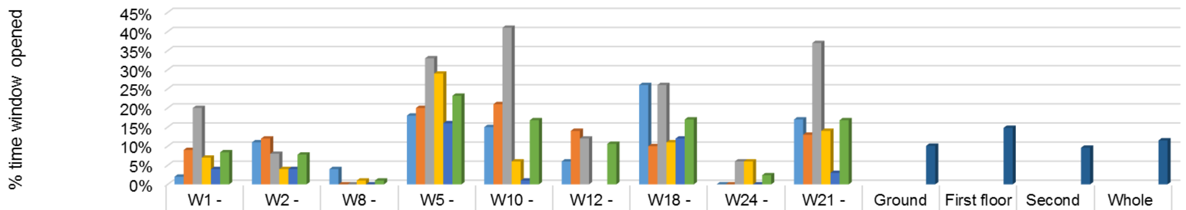


Figure 3- Percentage of indoor CO_2 levels over the standard

Some data losses as previously mentioned occurred due to the slippery surface on the window frames leading to the sensors not staying in place which has not been taken into calculation. The percentage of the window operation for the individual windows of the two buildings during the five months of monitoring was calculated alongside the average for different floors and the entire building(s) (Figures 4&5).

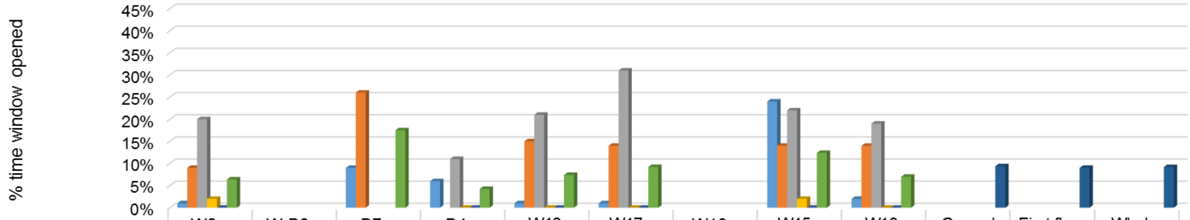
Building one:



	W1 - Dining room	W2 - Living room	W8 - Kitchen	W5 - Living room / office	W10 - Main bedroom	W12 - Bedroom 5	W18 - Master En-suite	W24 - Bedroom 3	W21 - Bedroom 4	Ground floor	First floor	Second floor	Whole building
May	2%	11%	4%	18%	15%	6%	26%	0%	17%				
June	9%	12%	0%	20%	21%	14%	10%	0%	13%				
July	20%	8%	0%	33%	41%	12%	26%	6%	37%				
August	7%	4%	1%	29%	6%		11%	6%	14%				
September	4%	4%	0%	16%	1%		12%	0%	3%				
Average 5 months	8.40%	7.80%	1%	23.20%	16.80%	10.60%	17%	2.40%	16.80%				
Average Floor										10.10%	14.80%	9.60%	11.50%

Figure 4- The percentage of window operations

Building two:



	W2 – Sitting room	W-D3 – Sitting room	D7 – Dining room	D4 – Dining room	W13 Bedroom 1	W17 - Bathroom	W16 – Bedroom 4	W15 - Bedroom 5	W18 - Bedroom 2	Ground floor	First floor	Whole building
May	1%		9%	6%	1%	1%		24%	2%			
June	9%		26%		15%	14%		14%	14%			
July	20%			11%	21%	31%		22%	19%			
August	2%			0%	0%	0%		2%	0%			
September	0%			0%	0%	0%		0%	0%			
Average 5 months	6.40%		17.50%	4.25%	7.40%	9.20%		12.40%	7%			
Average Floor										9.38%	9%	9.19%

Figure 5- The percentage of window operations

In general the windows were opened in the warmer months of the year as expected and had a similar opening average for each floor. Closer examination of the data underlined the very limited or total lack of window operation during the night even on the higher floors which could be due to security and noise implications. Therefore the night time cooling accounted for during the design stage and part of PHPP calculations was in reality non-existent for both of the buildings.

Although both buildings share a similar average percentage of window openings, Building One experienced a much higher percentage (21%) of overheating meaning the effectiveness of natural ventilation achieved through the use of windows was not similar. This was expected to be due to the way the windows were opened and therefore limiting the airflow. Building One's windows were generally opened on the tilt whereas Building Two's patio windows at the rear of the property were usually opened fully. Airflow through the windows was also restricted by the use of blinds which in the case of Building One are internal as well as external. The blinds were not monitored as part of this research, however the high level of the blind operation was noted during several visits to the building. In addition, when occupants were asked whether they would leave the windows open during unoccupied hours, the answer was 'never' for both buildings.

4. A closer look into PHPP calculations

The PHPP calculations for both buildings using PHPP7 had indicated no overheating and this necessitated further investigation, specifically in the case of Building One, based on the monitoring results. Internal heat gains and window operations from the PHPP calculations were re-examined using the monitoring data and the updated equipment schedule. The standard internal gain of 2.1W/m^2 from PHPP7 was recalculated using PHPP8 for the summer periods. PHPP8 takes into consideration, the extra heat gain from the MVHR unit (if placed inside the thermal envelope), as well as the hot water storage and distribution. The internal heat gain calculations from PHPP8 (also taking the as built equipment schedule into consideration), resulted in 3.65W/m^2 and 3.50W/m^2 of internal heat gains for Building One and Two respectively. Based on recalculations in PHPP8, the higher internal heat gain therefore resulted in a higher percentage of overheating at 8.5% for Building One and 7.6% for Building Two.

The overheating percentage calculated from PHPP8 however did not match the monitored data and consequently, the natural ventilation calculations used in PHPP were compared with the window monitoring results. The PHPP calculations for both buildings assumes 0.22 air change per hour for night time cooling through window opening, but this was almost non-existent based on the monitoring results. As a result the night time ventilation was removed in PHPP8 and replaced with 0.15 air change per hour additional natural ventilation using windows during the daytime for the summer period.

The shading in Building Two was also adjusted as part of this exercise in order to reflect the retrofitted shading implemented by the client. Consequently, the revised PHPP8 calculations indicated a higher overheating percentage of 19.4% for Building One and 0% for Building Two which is more in line with the data recorded during the monitoring period of 21.13% and 0.26%.

5. MVHR summer bypass option (PHPP Calculation & Monitoring Data)

The original calculation for Building One using PHPP7 had not indicated any overheating potential in comparison to the 8.5% of overheating estimated by PHPP8. Both PHPP calculations use the option for the summer bypass for the MVHR alongside the specified 0.22 air change/h for night time cooling using the windows. In order to examine the impact of the lack of summer bypass option on the overheating percentage, recalculation was undertaken keeping all the data the same, except the summer bypass for the MVHR. The summer bypass option was changed to 'always' meaning that the MVHR would not be using this option.

Without the summer bypass option in PHPP8, the predicted overheating potential increases from 8.5% to over 17% and more importantly it exceeds the allowable 10% limit for Passivhaus standard. Therefore if the MVHR unit specified for this building did not benefit from the summer bypass option then the building would have needed to look at other areas to reduce the summer temperature and the additional heat gain from the unit in order to satisfy the standards and provide a comfortable environment for its occupants.

The additional heat gain from the MVHR unit was examined by monitoring the indoor temperatures in the MVHR room. The MVHR as previously mentioned, is located inside a large cupboard in the north side of the building with no glazing and it is accessed from the shower room.

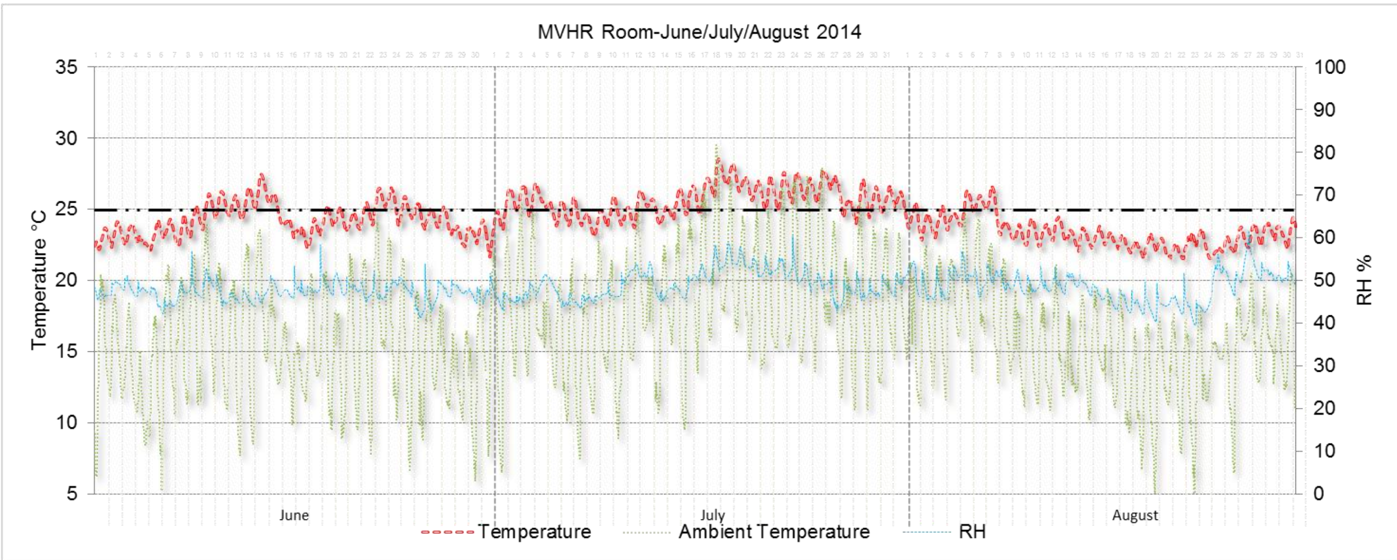


Figure 6- Measured indoor temperature and RH, comparison to ambient temperature (Building One)

The temperatures recorded were found to be above the 25°C limit during this period especially for the month of July. The monitored space houses the MVHR unit only, with no further internal or external heat gain. The overheating in this area was calculated to be just over 26% for June, 67.6% for July and 11.7% during the month of August (Figure 6). The highest temperature during July was recorded to be over 28.5°C highlighting the importance of taking the extra heat gain created by the use of MVHR into consideration during the design stage in order to minimise the overheating potential.

Geographically, Building Two is located to the north of Building One and therefore, benefits from a cooler local climate as well as a lower airtightness level due to the nature of the refurbishment building and EnerPhit standard. Building Two also benefits from higher thermal mass in comparison to Building One, providing the opportunity for undertaking a comparative assessment. The calculation carried out using PHPP8 for Building Two had highlighted an overheating percentage of 7.6% with the same night time ventilation rate as per Building One of 0.22 air change/h using the windows as per the original PHPP calculation.

Recalculation using the no summer bypass option (keeping all the other settings same) resulted in an increase in the overheating potential similar to the first building from 7.6% to 19.8%. Likewise for this building, the lack of summer bypass option can potentially result in a higher overheating percentage to almost double the maximum 10% allowed under the Passivhaus standard even with the cooler climate used in PHPP for this building. Although the location of the MVHR for this building is also within the thermal envelope, however it is located in a very large loft space used as storage only with no further internal or external heat sources.

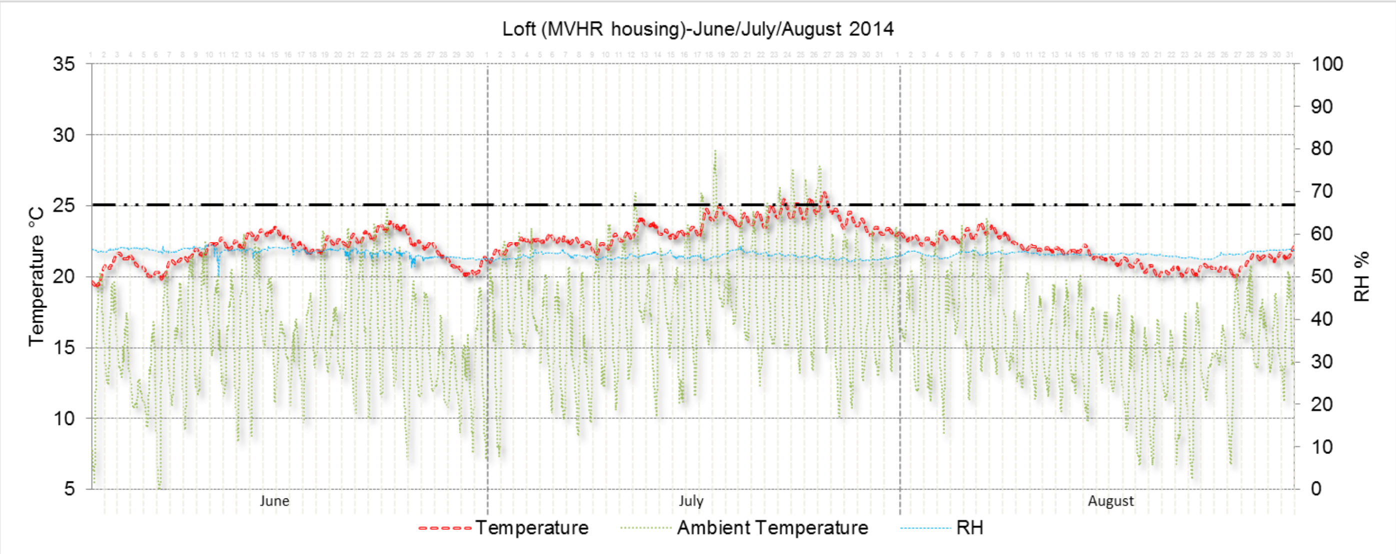


Figure 7- Measured indoor temperature and RH, comparison to ambient temperature (Building Two)

As per Building One, the monitoring data shows additional heat gain from the MVHR unit in Building Two (Figure 9). However, overall temperatures were lower and this could be attributed to the large area of the loft helping to regulate the temperatures. The temperatures were over the limit for 5.68% in July only, with a maximum temperature reaching 25.9°C.

6. Investigation into MVHR duct insulation

There is no requirement under the Passivhaus standard to insulate the internal air ducts leading out of the MVHR if the unit does not have a post heater. Therefore as the internal temperature rises during the warmer periods of the year, the incoming fresh air temperatures can be affected by the indoor temperature similar to the MVHR heat exchanger. To examine the potential influence of the indoor temperature on the incoming fresh air's temperature (from MVHR) during summer time, the two buildings' main bedroom and the living room indoor temperatures were monitored alongside the incoming fresh air temperatures at the MVHR outlet. The hourly indoor temperature of main bedroom and living room for both buildings was compared to the hourly temperature of the MVHR fresh air outlet into both spaces during June, July and August (Figures 8 & 9)

Building One:

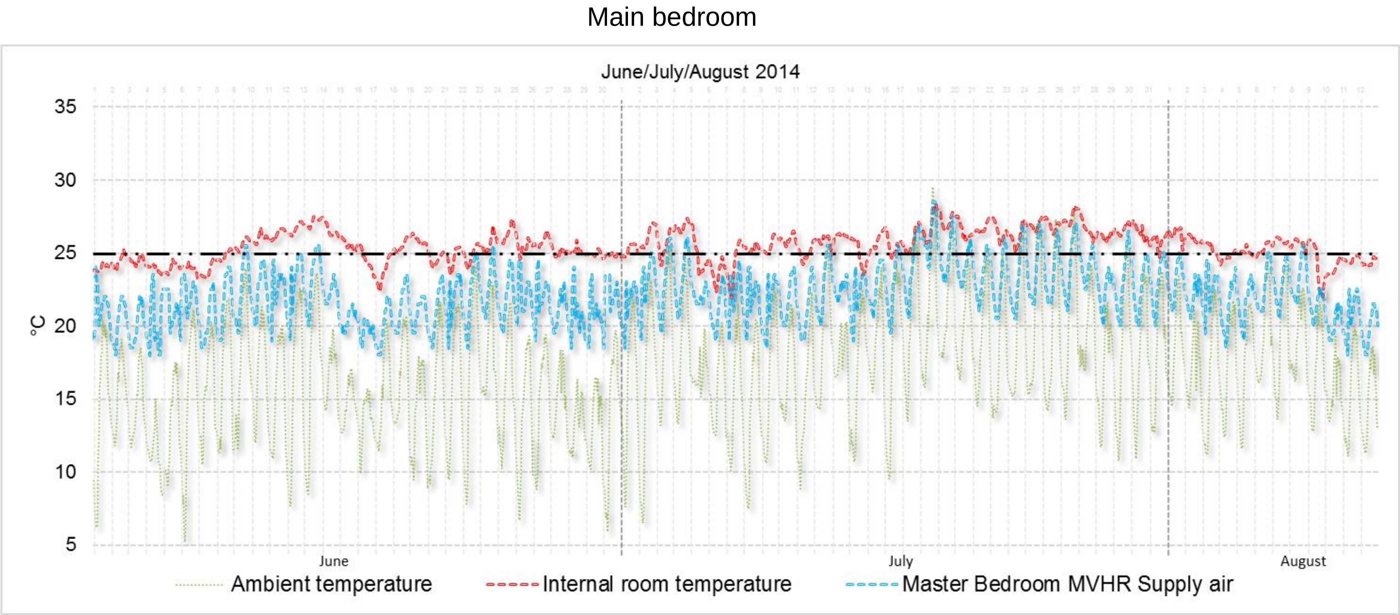


Figure 8- Hourly supply air temperature in relation to ambient and the internal temperature – Main Bedroom – Building One

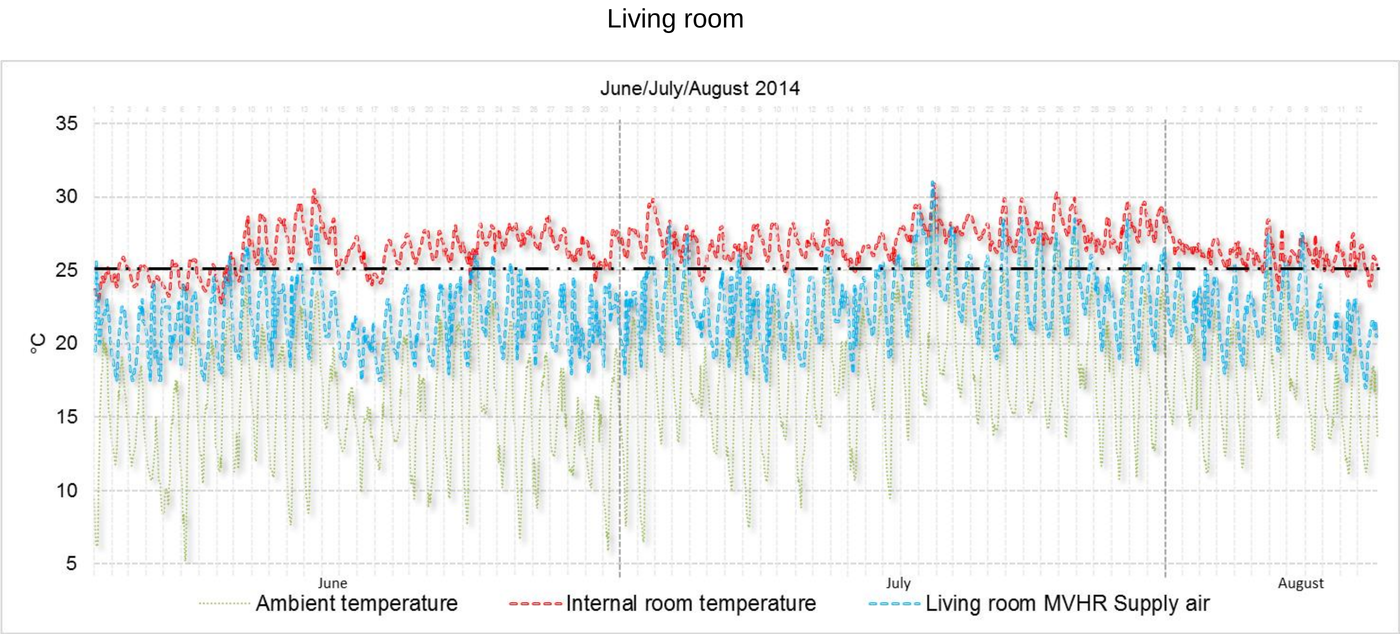


Figure 9- Hourly supply air temperature in relation to ambient and the internal temperature – Living Room - Building One

Building Two:

Main bedroom

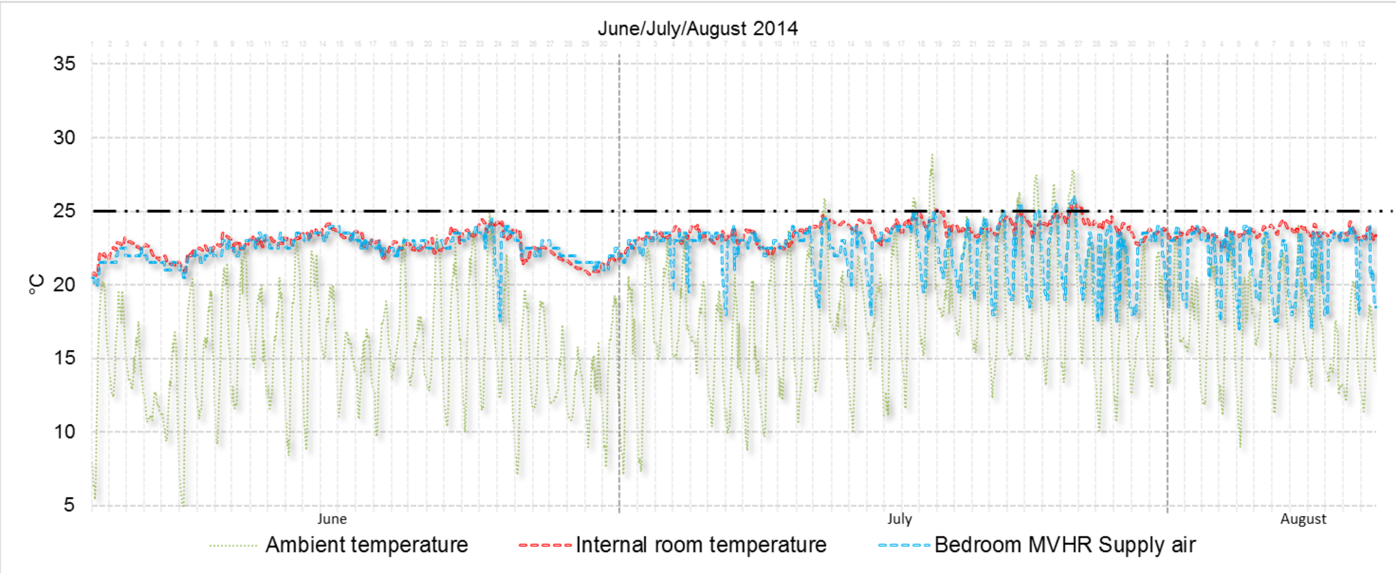


Figure 10- Hourly supply air temperature in relation to ambient and the internal temperature – Main bedroom– Building Two

Living room

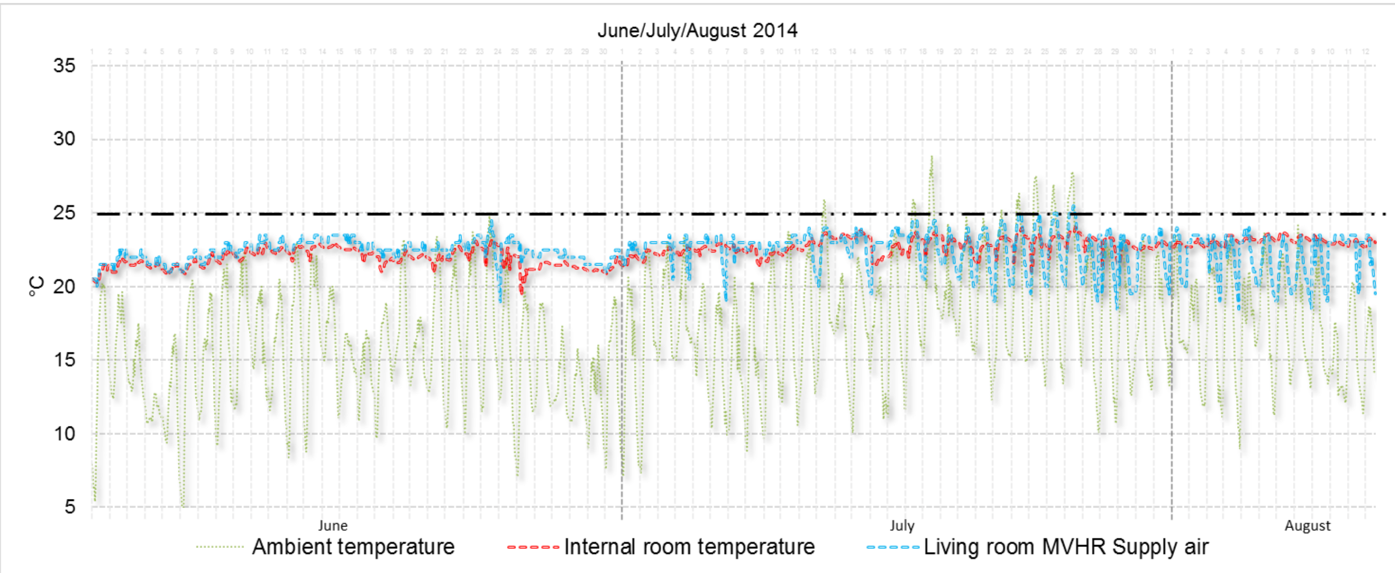


Figure 11- Hourly supply air temperature in relation to ambient and the internal temperature - Living Room – Building Two

The MVHR summer bypass option for Building One and Building Two is activated at 21°C and 23°C respectively (comfort temperature). Therefore if the indoor temperature exceeds this limit (and the ambient temperature is lower than the indoor temperature), the MVHR bypasses the heat exchanger allowing cooler outdoor air to enter the building directly. However the heat exchanger would be reactivated at night if the indoor temperature falls below the 'comfort temperature', without consideration for possible night time cooling as might be desirable in the summer. This is crucial especially if night time ventilation was factored into the design for cooling the internal thermal mass of the building.

The MVHR unit in Building One is located in the second floor cupboard with all ducts running within the ceiling voids and as can be seen from Figures 8 & 9 despite the summer bypass option being activated, the incoming fresh air temperatures were in most cases above ambient temperatures. The measured temperatures at the MVHR outlet of the main bedroom and living room indicate that the incoming fresh air temperature is influenced (increased) by some other source. One of the likely reasons could be the lack of insulation around the MVHR ducts leading from the unit to the individual supply and intakes within the building; and therefore as the indoor temperature increases, the fresh air is pre warmed in the ducts before entering the rooms.

The loft space in Building Two, is part of the thermal envelope (used as storage) and houses not only the MVHR unit but the majority of the duct runs. The temperatures in the loft space stay relatively stable and low at an average of 22.3°C. The lower temperature in the loft could be minimising the impact of the lack of insulation around the ducts and hence the temperature of fresh air entering both the bedroom and the living room, almost always stays below the 25°C limit and within the summer bypass temperature (Figures 10 & 11). However, as with Building One, the benefit of night time cooling is not realised because the MVHR summer bypass has been automatically deactivated.

7. The microclimate surrounding the MVHR air intake

The importance of material property in reference to its absorbency and emissivity alongside the orientation has been recognised in PHPP8 by the new requirements for information on the Area Sheet for walls, roof etc. (Passive House Institute, 2013). However there is no reference to the orientation, shading and type of material used around the fresh air intake for the MVHR system. To examine the possible effect of the material properties (e.g. thermal mass, solar absorbency, orientation and shading) on incoming fresh air, a thermal imaging camera was used to record the surface temperature around the MVHR intake.

The MVHR intake for both buildings is located on the northeast wall (20° East of North) making the two buildings highly comparable using different wall finishes. Building One's wall is constructed with lightweight materials and finished with dark coloured tiles mounted on battens, making the thermal mass around the fresh air intake limited. Building Two's wall on the other hand benefits from a high level of thermal mass internally, however it is insulated externally with a light coloured render finish, which reduces the effective thermal mass around the MVHR intake.

Measurements of the hourly surface temperatures for the materials surrounding the fresh air intake were obtained on 16th and 17th July 2014 for Building One and Building Two respectively and have been analysed in relation to the ambient temperature (Figures 12 & 13).

Building one

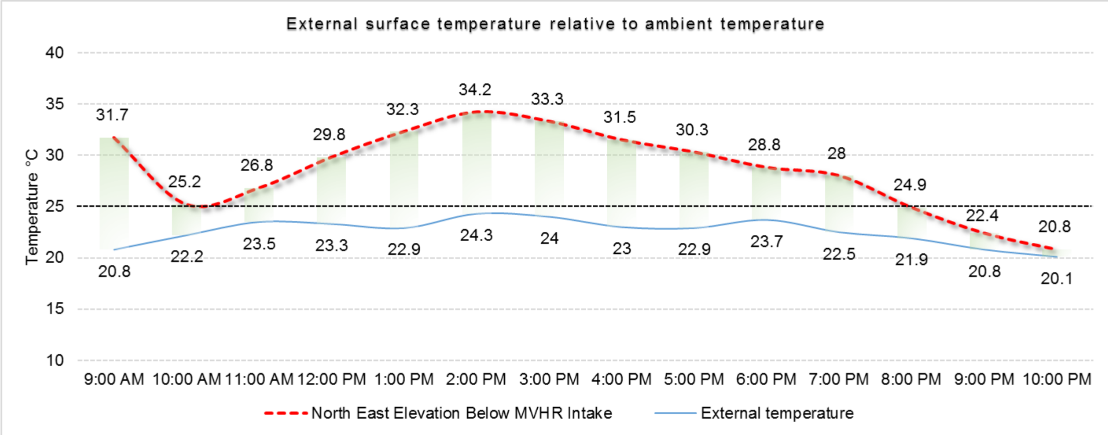


Figure 12- Surface temperature in respect to ambient temperature

Building two

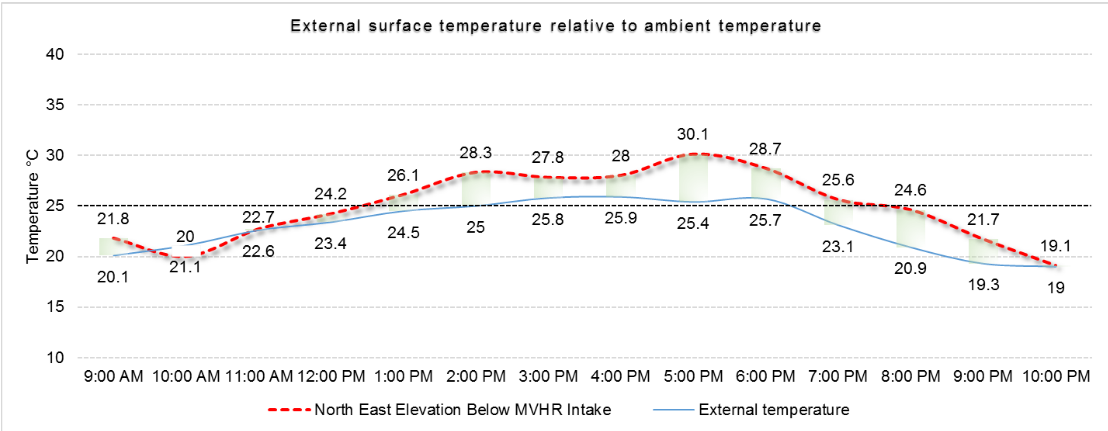


Figure 13- Surface temperature in respect to ambient temperature

As the MVHR air intake for both buildings is on the northeast façade, the effect of the direct sunlight is limited during the early morning hours, when the surface material temperature was recorded to be above the ambient temperature. As the sun moves around the building, a drop in temperature occurs at around 10:00am for both buildings. Despite the fact that the ambient temperature on the 17th (when Building Two was monitored), was slightly higher than the 16th, the surface temperature of the light coloured render was lower and was less effected by direct solar gain (Figure 13). In either case the lack of thermal mass led to a gradual drop in surface temperatures during the evenings, almost matching ambient temperature at night.

The importance of orientation and shading in respect to surface temperature and how that could affect the temperature of ambient air, was found to be significant. For instance, the maximum surface temperature recorded on the northeast façade for Building One was just over 34°C when the ambient temperature was 24.3°C, at 2:00pm giving a differential of almost 10°C. However, the surface temperature of the southeast façade (made of the same material and finish) was recorded to be over 52°C, giving a differential of around 28°C (Figures 14 & 15). Similarly the maximum surface temperature for Building Two was recorded at 5:00pm and was 30.1°C when the external temperature reached 25.4°C (a temperature difference of less than 5°C). This wall was much cooler than the southwest wall that was under direct solar radiation which recorded a surface temperature of 43°C during the same period, even though they were made of the same construction material (Figures 16 & 17).

Building One:

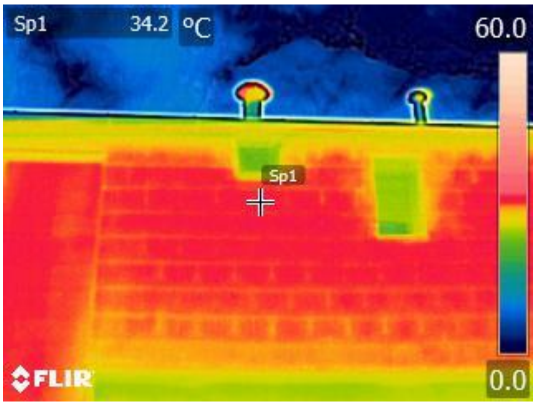


Figure 14- Northeast wall – MVHR intake

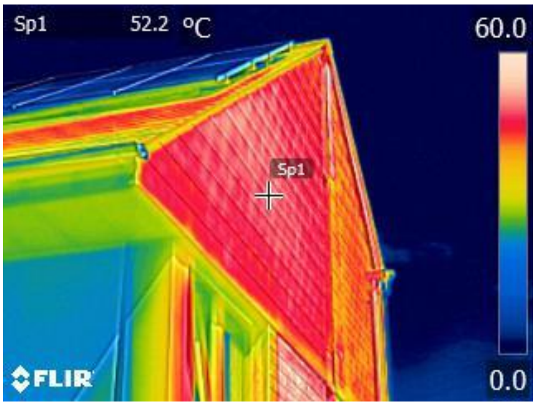


Figure 15- Southeast wall

Building Two:

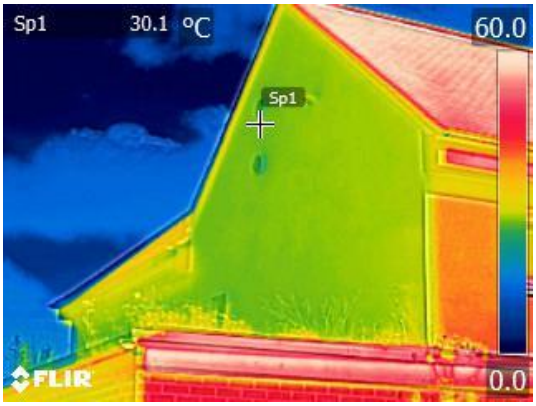


Figure 16- Northeast wall – MVHR intake

Figure 17- Southwest wall

The effect of material surface temperatures on the incoming fresh air in the master bedroom and living room fresh air outlet, was examined for Building One and Building Two using the data obtained from monitoring in comparison to the ambient temperature (Figures 18 to 21).

Building One:

Main bedroom

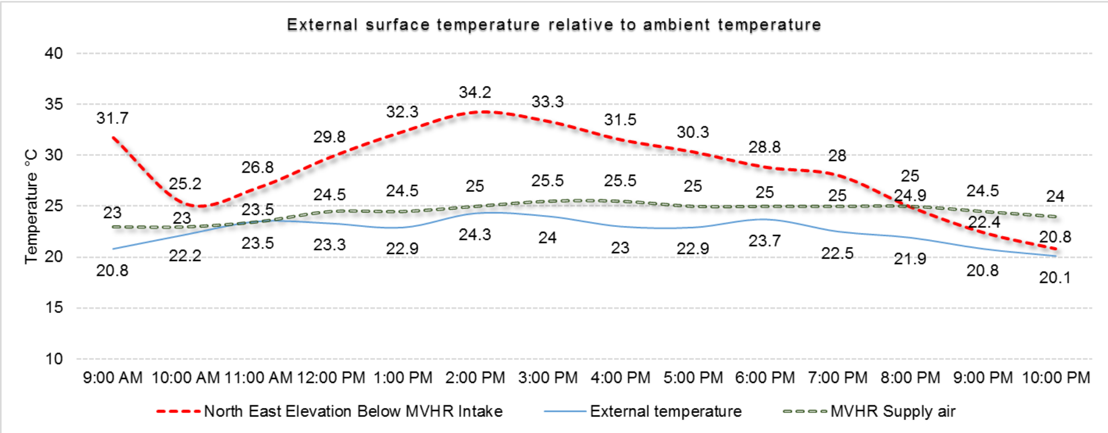


Figure 18- MVHR intake temperature in relation to ambient & surface temperature

Living room

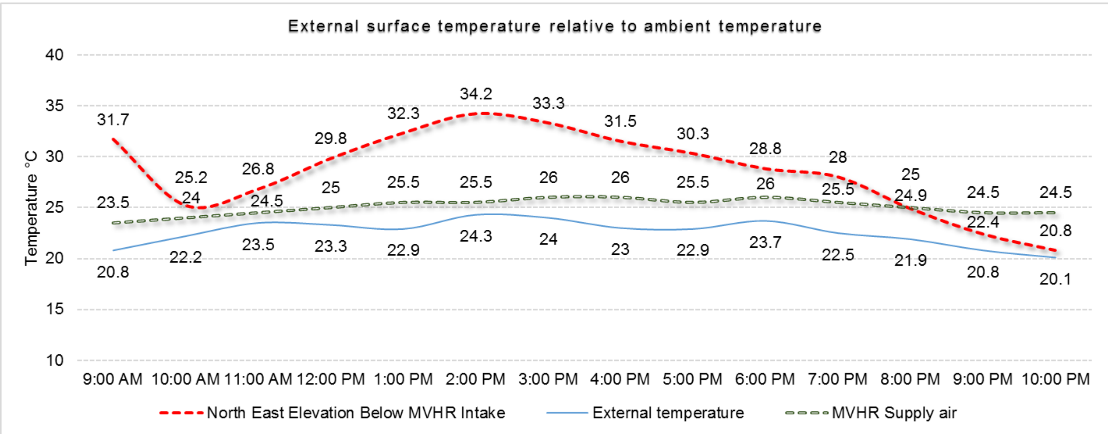


Figure 19- MVHR intake temperature in relation to ambient & surface temperature

Building Two:

Main bedroom

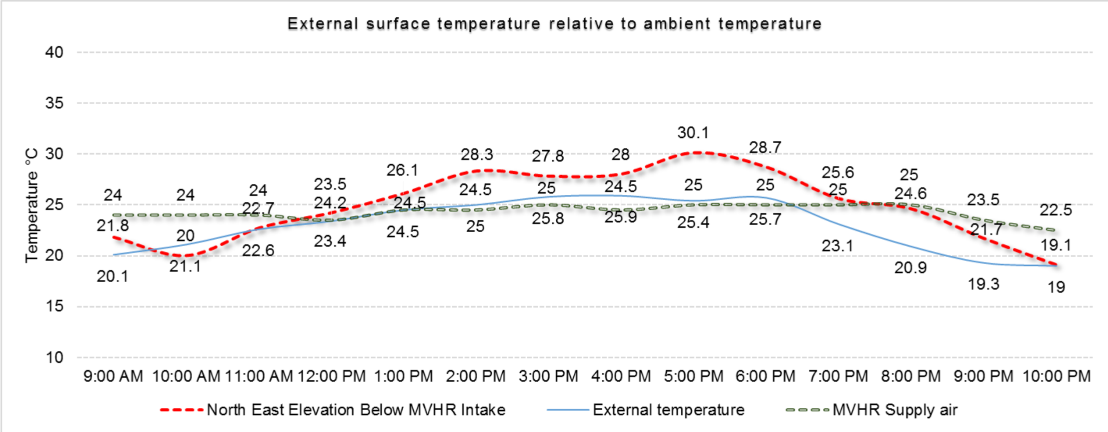


Figure 20- MVHR intake temperature in relation to ambient and surface temperature

Living room

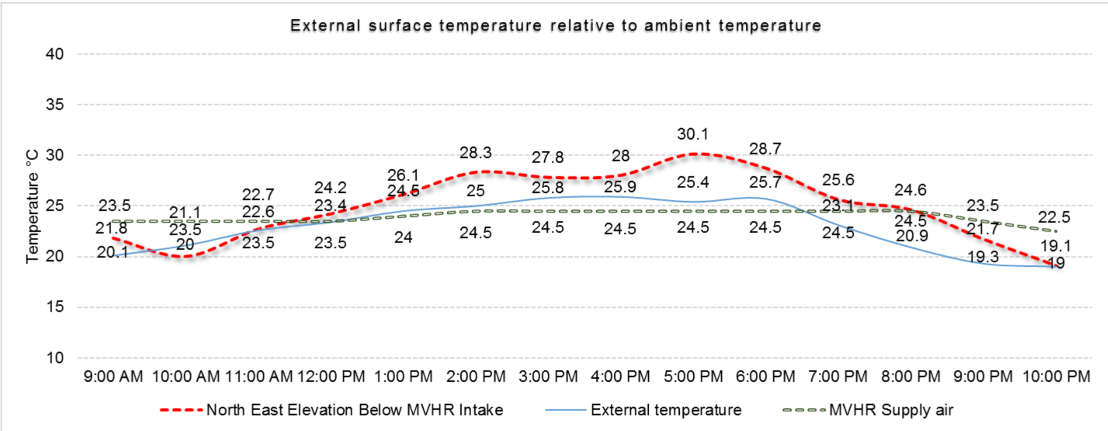


Figure 21- MVHR intake temperature in relation to ambient and surface temperature

The incoming fresh air of Building One was always above the ambient temperature despite the MVHR summer bypass being activated indicating the possible effect of the higher material surface temperature surrounding the MVHR fresh air intake. The ambient temperature was below 25°C for this period, however the incoming fresh air temperature from the MVHR was above this limit in the main bedroom and the living room at mid-day when the material surface temperature was at its highest. This is also true for

Building Two, however the effect was less and at mid-day the incoming fresh air temperature is close to the ambient temperature and at some points of the day was slightly below. Moreover even though the ambient temperature was recorded above 25°C, the MVHR incoming fresh air did not pass this 25°C limit indicating the higher effectiveness of the summer bypass option for Building Two's MVHR.

During the latter part of the day when the ambient temperature falls, the lack of thermal mass around the MVHR fresh air intake helps in reducing material surface temperature to be similar to the ambient temperature. However the incoming fresh air temperature from the MVHR was not necessarily reduced and was recorded to be around 24°C and 23°C for the two buildings respectively. It can be concluded that the MVHR summer bypass has been deactivated leading to heat being recovered from the higher indoor temperature and consequently reducing the possible cooling.

8. Discussion

The two case study buildings are very comparable in treated floor area as well as the ventilation volume, one built to Passivhaus standard and the other refurbished to EnerPhit standard. The specific heat demand was calculated to be 11kW/(m^{2}a) and 20 kW/(m^{2}a) respectively with a considerable difference in their airtightness level. The airtightness for Building One was tested to be 0.07 air change at 50 Pascal whereas Building Two was recorded at 1 air change at 50 Pascal. Both buildings continue using the MVHR during the summer period and benefit from summer bypass option set at 21°C and 23°C respectively. The MVHR efficiency however is almost 10% better in Building Two. Both buildings' envelope U-Values and their glazing properties sit comfortably within the Passivhaus standard in the UK. However Building One is designed with more glazing towards the South with around 10m^2 more glazing area in total.

The monitoring results indicated a high level of overheating in Building One and a lower percentage in the case of Building Two. The overheating percentage was even higher in individual areas reaching as high as 92.5% in the kitchen and 71.4% in the living room. Moreover the lower stories experienced higher temperatures in comparison to the levels above which was true for both buildings. Importantly averaging the total overheating for the entire building over the whole year reduces the percentage of the overheating considerably which is also used in the PHPP calculation. The average overheating percentage for Building One over the year (taking no further overheating into consideration) would translate to just over 21%

which is much lower compared to the individual areas. Nevertheless, the 21% is more than double the 10% allowable limit for the Passivhaus standard.

Monitoring the indoor CO_2 levels indicated a sufficient ventilation rate in the living room of both buildings. However the CO_2 levels in the main bedrooms for both properties were recorded to be over the required limit during this period reducing in percentage during the warmest months when the windows were open more often. The majority of high CO_2 levels were recorded to be during the night time when the occupants were sleeping.

The results from monitoring the windows highlighted very small or no night time ventilation in the case of both buildings. In general the windows were opened the most during the warmest period of the year and similar in percentage at different levels of the buildings. The average of the window opening for both buildings is also very similar highlighting the effectiveness of window opening in the case of Building Two. The ground floor windows in Building Two were opened fully whereas almost all the windows were opened on tilt inwards (85mm) Building One as observed from the site visits. The restriction in air flow by the heavy use of internal and external blinds in Building One was also observed. Moreover both buildings' occupants stated that the windows were never left open when the buildings where unoccupied.

The recalculation using the latest PHPP at the time of the research regarding the internal heat gains during the summer, indicated higher internal heat gains for both buildings at 3.65W/m^2 and 3.50W/m^2. The higher internal heat gain can also contribute to the overheating percentage alongside the assumption of window operation during the design stage using PHPP. Amendments were made to the PHPP calculation reflecting the actual window operation and shading patterns which resulted in a much closer percentage of overheating for both buildings in comparison to the monitored data.

The possible contribution to summer overheating from lack of summer bypass option was also investigated alongside the extra heat gain from the unit itself during the warmer part of the year. The lack of summer bypass option resulted in an increase of overheating percentage to 17% and 19.8% using PHPP8 for Building One and Two respectively. Both MVHR units are located in storage areas with no further internal or external gains. MVHR room hourly temperature recordings in Building One were over 25°C for 26% of the time in June, 67.6% and 11.7% in July and August. However the MVHR in Building Two is located in a large loft space and therefore the heat gained from the unit is dissipated in a larger area resulting in 5.68% of overheating in July only.

During the night the MVHR summer bypass is automatically deactivated to ensure the incoming temperature is as close as possible to 20°C which therefore reduces the benefit from night cooling. Furthermore the lack of insulation around the internal ducts can increase the incoming fresh air temperature which would consequently contribute to higher indoor temperature. In order to better understand the changes in temperature, further investigation would be necessary to examine the air temperature at the point of entering the MVHR, immediately after exiting the unit as well as the entry point into the rooms, to establish the changes in the temperature at different stages.

Moreover the location and material surrounding the MVHR intake can also influence the incoming fresh air temperature. The Northeast location for the two buildings' MVHR fresh intake reduces the local temperature whereas lack of thermal mass of the material surrounding the intake ensures the drop in temperature in relation to the ambient temperature. Comparing both buildings' surface material temperatures highlights the higher absorbency of the darker material of Building One especially under direct solar gain. The highest material surface temperature below the MVHR air intake was recorded to be 18°C lower than the same material on the Southeast facade of Building One and 13°C in the case of Building Two. Moreover when examining the incoming fresh air temperature, the influence of higher local temperature surrounding the MVHR intake was noted especially during the cooler part of the day.

9. Conclusion and recommendations

The monitoring of the two case study buildings identified overheating for both buildings during the summer of 2014. However Building Two was over the limit for only 0.26% of the year when Building One was overheated for 21% of the year. Building Two benefits from a high level of thermal mass and lower airtightness level alongside less glazing area in comparison. This as well as a cooler climate and higher client awareness, collectively could be the influence on lower overheating potential during the summer period. Even though windows were operated less in Building Two, higher natural ventilation was achieved through more effective window opening and therefore a lower overheating percentage. The window opening in Building One was more often on tilt, whereas the higher air flow in Building Two was achieved through fully opened patio doors and a lack of night time window operation was observed (in both buildings) which is in contrast to the PHPP calculations.

Window monitoring has allowed a better understanding of end user behaviour as well as helping to amend the PHPP models to be closer to data collected for both buildings. The lack of night time window opening was concluded to be due to security and noise concerns even though both buildings are located in quiet residential areas. The lower reliance on window operation due to noise and security implications is also highlighted in PHPP8’s manual (Passive House Institute, 2013). During the design stage perhaps more effort should be considered for summer shading and window operation and different percentages of natural ventilation should be tested as part of the standard PHPP option highlighting the higher potential of overheating due to the lack of window opening and the end user's behaviour.

The need for a summer bypass option on the MVHR also should perhaps be emphasized by the Passivhaus standard. This research has highlighted the possible extra overheating potential due to the lack of summer bypass option using PHPP8 calculations which has led in an increase of possible overheating in excess of 10%. In order to maximise the benefit of the incoming fresh air in cooling the building through the use of MVHR during the summer, the duct runs internally can also play an important role. The lack of insulation around the ducts can potentially increase the incoming fresh air temperature leading to a reduction of possible cooling from the incoming fresh air. This was demonstrated by the data obtained from the two case study buildings' room temperature and the incoming fresh air temperature at the outlet of the MVHR entering the living room and the main bedroom.

Furthermore the location of the MVHR air intake in reference to orientation and the material properties adjacent to the intake was investigated which further can influence the temperature of the incoming fresh air. The direct solar gain and material absorbency can have an effect on the material surface temperature whilst the material's thermal mass can influence its temperature in the latter part of the day. This can potentially reduce the desired night time cooling effect as well as increase the temperature of the incoming fresh air during the warmer part of the day. Whilst the benefit of a highly efficient MVHR unit can help in reducing the energy demand during the winter, the careful design regarding the location of the intake and the properties of the material immediate to the intake alongside the summer bypass option can help in not only eliminating any extra unwanted heat gain but also help in the possible cooling effect during the warmer periods.

In order to ensure lower summer temperatures in buildings built to Passivhaus standard, higher attention is required to maximise the cooling effect achieved from the ventilation whether from the MVHR unit or naturally using the windows. The location of the MVHR intake and the material surrounding it as well as reliance on night time ventilation can have a high impact on the potential overheating during the warmer part of the year.

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